Superluminal motions (and microwave propagation) in Special Relativity: Solution of the causal paradoxes.[†]

Erasmo Recami

Facoltà di Ingegneria, Università Statale di Bergamo, Dalmine (BG), Italy;
INFN–Sezione di Milano, Milan, Italy; and
C.C.S. and D.M.O./FEEC, State University at Campinas, S.P., Brazil.

Abstract – Some recent experiments, performed at Berkeley, Cologne, Florence and Vienna led to the claim that something seems to travel with a speed larger than the speed c of light in vacuum. Various other experimental results seem to point in the same direction: For instance, localized wavelet-type solutions of Maxwell equations have been found, both theoretically and experimentally, that travel with Superluminal speed. Even muonic and electronic neutrinos —it has been proposed— might be "tachyons", since their square mass appears to be negative; not to mention the apparent Superluminal expansions observed in the core of quasars and, recently, in the so-called galactic microquasars. In the first part of this paper we verify, on the basis of the numerical solution of Maxwell equations, that waves propagating down a microwave guide can travel with Superluminal group velocity, just confirming some of the previously mentioned experimental results. Then, we have to face the question of Superluminal motions within the theory of Special Relativity. It is not widely recognized that all such theoretical and experimental results do *not* place relativistic causality in jeopardy. For instance, it is possible (at least in microphysics) to solve also the known causal paradoxes, devised for "faster than light" motion. Here we show, in detail and rigorously, how to solve the oldest causal paradox, originally proposed by Tolman, which is the kernel of many further tachyon paradoxes. The key to the solution is a careful application of tachyon mechanics, as it unambiguously follows from Special Relativity.

Introduction. – Superluminal propagation has been observed in several areas of physics([1]). In electromagnetism, in particular, some recent experiments performed at Cologne([2]), Berkeley([3]), Florence and Vienna with evanescent waves ("tunnelling photons") led to the claim that evanescent modes can travel with a group velocity larger than the speed c

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of light in vacuum, thus confirming some older predictions([4]). Even more recently, some of the main experimental claims (e.g., in ([2])) have been verified([5]) just by solving the Maxwell equations with the requested boundary conditions.

Various other experimental results seem to point in the same direction: For instance, localized wavelet-type solutions of Maxwell equations have been found, both theoretically([1]) and experimentally([6]), that travel with Superluminal speed. Even muonic and electronic neutrinos —it has been proposed— might be "tachyons", since their square mass appears to be negative([7]); not to mention the apparent Superluminal expansions observed in the core of quasars([8]) and, recently, in the so-called galactic microquasars([9]). Nevertheless, all such data or results do *not* seem to place relativistic causality in jeopardy. In fact, when Special Relativity (SR) is not restricted to subluminal objects, so that it expands into the so-called Extended Relativity, one is left with a theory describing also Superluminal objects and waves on the basis of the ordinary postulates of SR. As far as the foundations of Extended Relativity are concerned, we shall only quote ref.([10]) and references therein. Here we shall mainly confine our attention to the fact that it is possible to solve (also) the known causal paradoxes, devised for "faster than light" motion, even if this is not widely recognized.

We shall come back soon to this point. First, however, let us briefly examine for instance the experiments in refs.([2]), by making recourse to work performed by A.Pablo L.Barbero and H.E. Hernández-Figueroa at UNICAMP.([5])

Theoretical verification of microwave Superluminal propagation. – The inset (a) in Fig.1 shows the waveguide used in those experiments. Launching a TE_{10} signal, limited in frequency by $\omega_{\rm m}$ such that $\omega_{\rm m} < \omega_{\rm c}$, where $\omega_{\rm c}$ is the cutoff frequency for the fundamental mode in the "undersized" waveguide (or "barrier"), those authors showed that the transit time of the signal along the barrier is independent of its length a. This agrees, incidentally, with the effect predicted by quantum mechanics for particle tunnelling([11]): an effect that we called "Hartman effect". Considering that purely evanescent waves travel in principle with infinite speed, the finite Superluminal speed encountered in those measurements can be attributed to the delay induced by the geometrical discontinuities present at the barrier edges. Using a spectrum analyzer, the transfer function associated with the barrier can be gotten by measuring the S-parameter. The phase of the transfer function for four different barrier lengths (40, 60, 80 1nd 100 mm) is shown in Fig.2(b); notice that such four curves are practically superposed.([5])

In order to check those experimental results, in ref.([5]) it was adopted a numerical

code based on the method of moments (MoM), widely used in the design of microwave filters and other devices by the Antennas Research Group at CPqD-Telebrás, Brazil. Such a code solves the Maxwell equations in the frequency domain, in presence of transitions associated with inductive (vertical) discontinuities only (Fig.1, inset *b*). Notice that the experimental setup in inset *a* of Fig.1, is not really very different, even if it takes into account also capacitive (horizontal) discontinuities: the latter, in fact, produce a transfer function whose phase, as a function of the frequency, is practically constant, and their magnitude is much smaller than the one produced by the inductive discontinuities.([12])

We adopted([5]) a pulse modulated by a Kaiser-Bessel window, producing a signal with a limited spectrum, between 8.2 and 9.2 GHz, similar to the input signal used in ([2]). The transfer functions were computed for barriers of 40, 60 and 100 mm. The phases of such functions are shown in Fig.2a: notice their superposition. The maximum magnitudes of the output pulses were 0.05743, 0.01248 and 0.00062 for the 40, 60 and 100 mm barriers, respectively. These values were normalized with respect to the maximum magnitude of the input pulse, and exhibit an error of less than 4% relative to the experimental results([2]). The computed phase (Fig.2a) and the measured one (Fig.2b) are in qualitative agreement; they differ by a shift of about 10 degrees, due —as already mentioned— to the capacity discontinuities, considered in the experiment and ignored in our simulations. Next, by using the Fourier transform, we computed([5]) the pulse propagation in the time domain: the transit time for the input signal to travel down the three different barriers (of 40, 60 and 100 mm) was *the same*: 115 ps. Figure 1 shows the output signals for the three barriers. In refs.([2]) the measured transit time was 130 ps; the difference of 15 ps may be due again to the capacity discontinuities.

In conclusion, just by solving the Maxwell equations, we can confirm the main experimental results in ([2]). In ref.([13]), experiments with two barriers suggest the possibility of long-distance Superluminal propagation: we shall examine that case elsewhere([5]). Here we want to discuss a more general question. If something can travel with a speed larger than the speed c of light in vacuum, as suggested not only by the previous considerations but also by the results known from the abovementioned three further sectors of experimental physics (see Appendix B), then one has to face the problem of Superluminal motions from the point of view of Special Relativity. We have already claimed that all the previous results do not seem to place relativistic causality in jeopardy. In fact, when Special Relativity (SR) is not restricted to subluminal objects, so that it expands into the so-called Extended Relativity, one is left with a theory describing also Superluminal objects and waves on the basis of the ordinary postulates of SR. As far as the founda-

tions of Extended Relativity are concerned, we shall only quote ref.([14–16]) and references therein, and in particular ref.([10]); while we shall expound what is necessary for our present purposes in the Sections below and in Appendix A.

Let us then pass to the problem of solving the causal paradoxes arising for for "faster than light" motions.

Superluminal motions and relativistic causality – In fact, claims exist since long that all the ordinary causal paradoxes proposed for tachyons can be solved([14–16]) (at least "in microphysics") on the basis of the "switching procedure" (swp) introduced by Stückelberg([17]), Feynman([17]) and Sudarshan([14]), also known as the reinterpretation principle: a principle which in refs.([10,15]) by Recami et al. has been given the status of a fundamental postulate of special relativity, both for bradyons [slower–than–light particles] and for tachyons. Schwartz,([18]) at last, gave the swp a formalization in which it becomes "automatic".

However, the effectiveness of the swp and of that solution is often overlooked, or misunderstood. Here we want therefore to show, in detail and rigorously, how to solve the oldest "paradox", i.e. the *antitelephone* one, originally proposed by Tolman([19]) and then reproposed by many authors. We shall refer to its recent formulation by Regge,([20]) and spend some care in solving it, since it is the kernel of many other paradoxes. Let us stress that: (i) any careful solution of the tachyon causal "paradoxes" has to make recourse to explicit calculations based on the mechanics of tachyons; (ii) such tachyon mechanics can be unambiguously and uniquely derived from SR, by referring the Superluminal ($V^2 > c^2$) objects to the class of the ordinary, subluminal ($u^2 < c^2$) observers *only* (i.e., without any need of introducing "Superluminal reference frames"); (iii) moreover, the comprehension of the whole subject will be substantially enhanced if one refers himself to the (subluminal, ordinary) SR based on the *whole* proper Lorentz group $\mathcal{L}_+ \equiv \mathcal{L}_+^\uparrow \cup \mathcal{L}_+^\downarrow$, rather than on its orthochronous subgroup $\mathcal{L}_+^\uparrow$ only [see refs.([21]), and references therein]. At last, for a modern approach to the classical theory of tachyons, reference can be made to the review article([10]) as well as to refs.([15,16]).

Before going on, let us mention the following. It is a known fact that in the time-independent case the (relativistic, non-quantistic) Helmholtz equation and the (non-relativistic, quantum) Schroedinger equation are formally identical([22]) [in the time-dependent case, such equations become actually different, but nevertheless strict relations still hold between some solutions of theirs, as it will be explicitly shown elsewhere([23])]: one impor-

tant consequence of this fact being that evanescent wave transmission simulates electron tunnelling. On the other side, a wave-packet had been predicted([24]) since long to tunnel through an (opaque) barrier with Superluminal group-velocity. Therefore, one could expect evanescent waves too to be endowed with Superluminal (group) speeds.([25]) The abovenamed experiments([1–3]), which seem to have actually verified such an expectation, are the ones that most attracted the attention of the scientific press.([26]) But they are not the only ones which seem to indicate the existence of Superluminal motions.[27]

Tachyon mechanics. – In refs.([28]) the basic tachyon mechanics can be found exploited for the processes: a) proper (or "intrinsic") emission of a tachyon T by an ordinary body A; b) "intrinsic" absorption of a tachyon T by an ordinary body A; where the term "intrinsic" refers to the fact that those processes (emission, absorption by A) are described *as they appear* in the rest-frame of A; particle T can represent both a tachyon and an antitachyon. Let us recall the following results only.

Let us first consider a tachyon moving with velocity $\boldsymbol{V}$ in a reference frame s_0. If we pass to a second frame s', endowed with velocity $\boldsymbol{u}$ w.r.t. (with respect to) frame s_0, then the new observer s' will see —instead of the initial tachyon T— an antitachyon $\overline{\mathrm{T}}$ travelling the opposite way in space (due to the swp: cf. Appendix A), if and only if

$$\boldsymbol{u} \cdot \boldsymbol{V} > c^2 \ . \tag{1}$$

Recall in particular that, if $\boldsymbol{u} \cdot \boldsymbol{V} < 0$, the "switching" does *never* come into play.

Now, let us explore some of the unusual and unexpected consequences of the trivial fact that in the case of tachyons it is

$$|E| = +\sqrt{\boldsymbol{p}^2 - m_0^2} \qquad (m_0 \;\; \text{real;} \;\; \boldsymbol{V}^2 > 1) \ , \tag{2}$$

where we chose units so that, numerically, $c = 1$.

Let us, e.g., describe the phenomenon of "intrinsic emission" of a tachyon, as seen in the rest frame of the emitting body: Namely, let us consider *in its rest frame* an ordinary body A, with initial rest mass M, which emits a tachyon (or antitachyon) T endowed with (real) rest mass([6]) $m \equiv m_0$, four-momentum $p^\mu \equiv (E_{\mathrm{T}}, \boldsymbol{p})$, and velocity $\boldsymbol{V}$ along the x-axis. Let M' be the final rest mass of body A. The four-momentum conservation requires

$$M = \sqrt{\boldsymbol{p}^2 - m^2} + \sqrt{\boldsymbol{p}^2 + M'^2} \qquad \text{(rest frame)} \tag{3}$$

that is to say [$V \equiv |\boldsymbol{V}|$]:

$$2M|\boldsymbol{p}| = [(m^2+\Delta)^2 + 4m^2M^2]^{\frac{1}{2}} \; ; \quad V = [1 + 4m^2M^2/(m+\Delta)^2]^{\frac{1}{2}} \; , \tag{4}$$

where [calling $E_{\rm T} \equiv +\sqrt{\boldsymbol{p}^2 - m^2}$]:

$$\Delta \equiv M'^2 - M^2 = -m^2 - 2ME_{\rm T} \; , \qquad \text{(emission)} \tag{5}$$

so that

$$-M^2 < \Delta \leq -|\boldsymbol{p}|^2 \leq -m^2 \; . \qquad \text{(emission)} \tag{6}$$

It is essential to notice that Δ is, of course, an *invariant* quantity, which in a generic frame s writes

$$\Delta = -m^2 - 2p_\mu P^\mu \; , \tag{7}$$

where P^μ is the initial four-momentum of body A w.r.t. frame s.

Notice that in the generic frame s the process of (intrinsic) emission can appear either as a T emission or as a $\overline{\rm T}$ absorption (due to a possible "switching") by body A. The following theorem, however, holds:([28])

Theorem 1: << A necessary and sufficient condition for a process to be a tachyon emission in the A rest-frame (i.e., to be an *intrinsic emission*) is that during the process the body A *lowers* its rest-mass (invariant statement!) in such a way that $-M^2 < \Delta \leq -m^2$. >>

Let us now describe the process of "intrinsic absorption" of a tachyon by body A; i.e., let us consider an ordinary body A to absorb *in its rest frame* a tachyon (or antitachyon) T, travelling again with speed V along the x-direction. The four-momentum conservation now requires

$$M + \sqrt{\boldsymbol{p}^2 - m^2} = \sqrt{\boldsymbol{p}^2 + M'^2} \; , \qquad \text{(rest frame)} \tag{8}$$

which corresponds to

$$\Delta \equiv M'^2 - M^2 = -m^2 + 2ME_{\mathrm{T}} \; , \qquad \text{(absorption)} \tag{9}$$

so that

$$-m^2 \leq \Delta \leq +\infty \; . \qquad \text{(absorption)} \tag{10}$$

In a generic frame s, the quantity Δ takes the invariant form

$$\Delta = -m^2 + 2p_\mu P^\mu \; . \tag{11}$$

It results in the following new theorem:

Theorem 2: << A necessary and sufficient condition for a process (observed either as the emission or as the absorption of a tachyon T by an ordinary body A) to be a tachyon absorption in the A-rest-frame —i.e., to be an *intrinsic absorption*— is that $\Delta \geq -m^2$. >>

We now have to describe the *tachyon exchange* between two ordinary bodies A and B. We have to consider the four-momentum conservation at A *and* at B; we need to choose a (single) frame relative to which we describe the whole interaction; let us choose the rest-frame of A. Let us explicitly remark, *however*, that —when bodies A and B exchange one tachyon T— the tachyon mechanics is such that the "intrinsic descriptions" of the processes at A *and* at B can a priori correspond to one of the following four cases([28]):

$$\begin{cases} 1) \quad \text{emission—absorption} \; , \\ 2) \quad \text{absorption—emission} \; , \\ 3) \quad \text{emission—emission} \; , \\ 4) \quad \text{absorption—absorption} \; . \end{cases} \tag{12}$$

Case 3) can happen, of course, only when the tachyon exchange takes place in the receding phase (i.e., while A, B are receding from each other); case 4) can happen, by contrast, only in the approaching phase.

Let us consider here only the particular tachyon exchanges in which we have an

"intrinsic emission" at A, and in which moreover the velocities $\boldsymbol{u}$ of B and $\boldsymbol{V}$ of T w.r.t. body A are such that $\boldsymbol{u} \cdot \boldsymbol{V} > 1$. Because of the last condition and the consequent "switching" (cf. Eq.(1)), from the rest-frame of B one will therefore observe the flight of an antitachyon $\overline{\mathrm{T}}$ *emitted* by B and absorbed by A (the *necessary* condition for this to happen, let us recall, being that A, B *recede* from each other).

More generally, the dynamical conditions for a tachyon to be exchangeable between A and B can be shown to be the following:

I) Case of "intrinsic emission" at A:

$$\begin{cases} \text{if } \boldsymbol{u} \cdot \boldsymbol{V} < 1 \,, & \text{then } \Delta_{\mathrm{B}} > -m^2 \quad (\longrightarrow \text{intrinsic absorption at B}); \\ \\ \text{if } \boldsymbol{u} \cdot \boldsymbol{V} > 1 \,, & \text{then } \Delta_{\mathrm{B}} < -m^2 \quad (\longrightarrow \text{intrinsic emission at B}). \end{cases} \tag{13}$$

II) Case of "intrinsic absorption" at A:

$$\begin{cases} \text{if } \boldsymbol{u} \cdot \boldsymbol{V} < 1 \,, & \text{then } \Delta_{\mathrm{B}} < -m^2 \quad (\longrightarrow \text{intrinsic emission at B}); \\ \\ \text{if } \boldsymbol{u} \cdot \boldsymbol{V} > 1 \,, & \text{then } \Delta_{\mathrm{B}} > -m^2 \quad (\longrightarrow \text{intrinsic absorption at B}). \end{cases} \tag{14}$$

Now, let us finally pass to examine the Tolman paradox.

The paradox. – In Figs.3, 4 the axes t and t' are the world-lines of two devices A and B, respectively, which are able to exchange tachyons and move with constant relative speed u, $[u^2 < 1]$, along the x-axis. According to the terms of the paradox (Fig.3), device A sends tachyon 1 to B (in other words, tachyon 1 is supposed to move forward in time w.r.t. device A). The device B is constructed so as to send back tachyon 2 to A as soon as it receives tachyon 1 from A. If B has to *emit* (in its rest-frame) tachyon 2, then 2 must move forward in time w.r.t. device B; that is to say, the world-line BA_2 must have a slope *lower* than the slope BA' of the x'-axis (where $\mathrm{BA}'//x'$): this means that A_2 must stay above A'. If the speed of tachyon 2 is such that A_2 falls between A' and A_1, it seems that 2 reaches A (event A_2) *before* the emission of 1 (event A_1). This appears to realize an *anti-telephone.*

The solution. – First of all, since tachyon 2 moves backwards in time w.r.t. body A, the event A_2 will appear to A as the emission of an antitachyon $\overline{2}$. The observer "t" will see his own device A (able to exchange tachyons) emit successively towards B the antitachyon $\overline{2}$ and the tachyon 1.

At this point, some supporters of the paradox (overlooking tachyon mechanics, as well as relations (12)) would say that, well, the description put forth by the observer "t" can be

orthodox, but then the device B is no longer working according to the stated programme, because B is no longer emitting a tachyon 2 on receipt of tachyon 1. Such a statement would be wrong, however, since the fact that " t " observes an "intrinsic emission" at A_2 *does not mean* that " t' " will see an "intrinsic absorption" at B! On the contrary, we are just in the case considered above, between eqs. (12) and (13): intrinsic emission by A, at A_2, with $\boldsymbol{u} \cdot \boldsymbol{V}_{\overline{2}} > c^2$, where $\boldsymbol{u}$ and $\boldsymbol{V}_{\overline{2}}$ are the velocities of B and $\overline{2}$ w.r.t. body A, respectively; so that *both* A *and* B experience an intrinsic *emission* (of tachyon 2 or of antitachyon $\overline{2}$) in their own rest frame.

But the tacit premises underlying the "paradox" (and even the very terms in which it was formulated) were "cheating" us *ab initio.* In fact, Fig.3 makes it clear that, if $\boldsymbol{u} \cdot \boldsymbol{V}_{\overline{2}} > c^2$, then for tachyon 1 *a fortiori* $\boldsymbol{u} \cdot \boldsymbol{V}_1 > c^2$, where $\boldsymbol{u}$ and $\boldsymbol{V}_1$ are the velocities of B and 1 w.r.t. body A. Therefore, due to the previous consequences of tachyon mechanics, observer "t'" will see B intrinsically *emit* also tachyon 1 (or, rather, antitachyon $\overline{1}$). In conclusion, the proposed chain of events does *not* include any tachyon absorption by B (in its rest frame).

For body B to *absorb* (in its own rest frame) tachyon 1, the world-line of 1 ought to have a slope *higher* than the slope of the x'-axis (see Fig.4). Moreover, for body B to *emit* ("intrinsically") tachyon 2, the slope of the of 2 should be lower than the x'-axis'. In other words, when the body B, programmed to emit 2 as soon as it receives 1, does actually do so, the event A_2 does happen *after* A_1 (cf. Fig.4), as requested by causality.

The moral. – The moral of the story is twofold: i) one should never *mix* the descriptions (of one phenomenon) yielded by different observers; otherwise —even in ordinary physics— one would immediately meet contradictions: in Fig.3, e.g., the motion direction of 1 is assigned by A and the motion-direction of 2 is assigned by B; this is "illegal"; ii) when proposing a problem about tachyons, one must comply([14]) with the rules of tachyon mechanics([25]); this is analogous to complying with the laws of *ordinary* physics when formulating the text of an *ordinary* problem (otherwise the problem in itself will be "wrong").

Most of the paradoxes proposed in the literature suffered the above shortcomings.

Notice once more that, in the case of Fig.3, neither A nor B regard event A_1 as the cause of event A_2 (or *vice-versa*). In the case of Fig.4, on the other hand, both A and B consider event A_1 to be the cause of event A_2: but in this case A_1 does chronologically precede A_2 according to both observers, in agreement with the relativistic covariance of the law of retarded causality.

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APPENDIX A: The Stueckelber–Feynman–Sudarshan "Switching Principle"

What follows refers equally well to bradyons and to tachyons. For simplicity, then, let us fix our attention in this Appendix only to the case of bradyons. Let us start from a positive-energy particle P travelling forward in time. As well-known, any orthochronows LT, $L^{\uparrow}$, transforms it into another particle still endowed with positive energy and motion forward in time. On the contrary, any antichronous (=non-orthochronous) LT, $L^{\downarrow} = -L^{\uparrow}$, will change sign –among the others– to the time-components of *all the four-vectors* associated with P. Any $L^{\downarrow}$ will transform P into a particle P' endowed in particular with negative energy *and* motion backwards in time (Fig.5). We are of course assuming that <<negative-energy objects travelling forward in time do *not* exist>>. (Elsewhere this Assumption has been given by us the status of a fundamental postulate).

In other words, SR together with the natural Assumption above, *implies* that a particle going backwards in time (Gödel([29])) (Fig.5) corresponds in the four-momentum space, Fig.6, to a particle carrying negative energy; and, vice-versa, that changing the energy sign in the latter space corresponds to changing the sign of time in the former (dual) space. It is then easy to see that these two paradoxical occurrences ("negative energy" and "motion backwards in time") give rise to a phenomenon that any observer will describe in a quite *orthodox* way, when they are –as they actually are– simultaneous (Recami([10,14–16]) and refs. therein).

Notice, namely, that: (i) every observer (a macro-object) explores space-time, Fig.5, in the positive t-direction, so that we shall meet B as the first and A as the last event; (ii) emission of positive quantity is equivalent to absorption of negative quantity, as $(-)\cdot(-) = (+)\cdot(+)$; and so on.

Let us now suppose (Fig.7) that a particle P' with negative energy (and, e.g., charge $-e$), travelling backwards in time, is emitted by A at time t_1 and absorbed by B at time $t_2 < t_1$. Then, it follows that at time t_1 the object A "looses" negative energy and negative charge, i.e. *gains* positive energy and positive charge. And that at time $t_2 < t_1$ the object B "gains" negative energy and charge, i.e. *looses* positive energy and charge. The physical phenomenon here described is nothing but the exchange *from* B *to* A of a particle Q with *positive* energy, charge $+e$, and travelling *forward* in time. Notice that Q has, however, charges *opposite* to P'; this means that the present "switching procedure" (previously called also "RIP") effects a "charge conjugation" C, among the others. No-

tice also that “charge”, here and in the following, means *any* additive charge; so that our definitions of charge conjugation, etc., are more general than the ordinary ones (Recami and Mignani,([30]) hereafter called Review I; Recami([10,15])). Incidentally, such a switching procedure has been shown to be equivalent to applying the chirality operation γ_5 (Recami and Ziino([31])).

Matter and Antimatter from SR – A close inspection shows that the application of any antichronous transformation $L^{\downarrow}$, together with the switching procedure, transforms P into an object

$$\mathrm{Q} \equiv \overline{\mathrm{P}} \tag{15}$$

which is indeed the *antiparticle* of P. We are saying that *the concept of antimatter is a purely relativistic one*, and that, on the basis of the double sign in $[c = 1]$

$$E = \pm\sqrt{\boldsymbol{p}^2 + m_0^2}, \tag{16}$$

the existence of antiparticles could have been predicted already in 1905, exactly with the properties they actually exhibited when later discovered, *provided that* recourse to the “switching procedure” had been made. We therefore maintain that the points of the lower hyperboloid sheet in Fig.6 –since they corresponds not only to negative energy but also to motion backwards in time– represent the kinematical states of the *antiparticle* $\overline{\mathrm{P}}$ *of* the particle P represented by the upper hyperboloid sheet).

Let us stress that the switching procedure not only can, but *must* be enforced, since any observer can do nothing but explore spacetime along the positive time direction. That procedure is an improved translation into a purely relativistic language of the Stückelberg–Feynman([17]) “Switching principle”. Together with our Assumption above, it can take the form of a “Third Postulate”: ⟨⟨Negative-energy objects travelling forward in time do *not* exist; any negative-energy object P travelling backwards in time can and must be described as its antiobject $\overline{\mathrm{P}}$ going the opposite way *in space* (but endowed with positive energy and motion forward in time)⟩⟩. Cf. e.g. Caldirola and Recami([32]), Recami([10,15]) and references therein.

Concluding remark of Appendix A – Let us go back to Fig.5. In SR, when based only on the two ordinary postulates, nothing prevents a priori the event A from influencing the event B. Just to forbid such a possibility we introduced our Assumption together with the Switching procedure. As a consequence, not only we eliminate any particle-motion

backwards in time, but we also "predict" and naturally explain within SR the existence of antimatter.

In the case of tachyons the Switching procedure was first applied by Sudarshan and coworkers([14]); see e.g. ref.([15]) and refs. therein.

APPENDIX B: Experimental data possibly related to Superluminal motions.

The question of Super-luminal objects or waves [tachyons: a term coined by G.Feinberg] has a long story, starting perhaps with Lucretius' *De Rerum Natura* (cf., e.g., book 4, line 201). Still in pre-relativistic times, let us recall e.g. the papers by A.Sommerfeld (quoted in refs.([10,33])). In relativistic times, our problem started to be tackled again essentially in the fifties and sixties, in particular after the papers by E.C.George Sudarshan et al., and later on by E.Recami, R.Mignani, et al. [who coined the term bradyons for slower-than-light objects, and rendered the expressions subluminal and Superluminal of popular use by their works at the beginning of the seventies], as well as by H.C.Corben and others (to confine ourselves to the *theoretical* researches). For references, one can check pages 162-178 in ref.([10]), where about 600 citations are listed; as well as the large bibliographies by V.F.Perepelitsa([34]) and as the book in ref.([16]). In particular, for the causality problems one can see refs.([10,15]) and references therein, while for a model theory for tachyons in two dimensions one can be addressed to refs.([10,17]). The first experiments looking for tachyons were performed by T.Alväger et al.; some citations about the early experimental quest for Superluminal objects may be found e.g. in refs.([35]).

The subject of tachyons is presently returning after fashion, especially because of the fact that four different experimental sectors of physics *seem* to indicate the existence of Superluminal objects. One of such sectors has been already mentioned by us. We wish to put forth in the following some information (mainly bibliographical) about the experimental results obtained in the other sectors.

Second - Negative Mass-Square Neutrinos – Since 1971 it was known that the experimental square-mass of *muon*-neutrinos resulted to be negative (with low statistical significance, but systematically). If confirmed, this would correspond (within the ordinary, naïve approach to relativistic particles) to an imaginary mass and therefore to a Superluminal speed; in a non-naïve approach,([10]) i.e. within a Special Relativity theory extended to include tachyons [Extended Relativity (ER)], the free tachyon "dispersion relation" becomes $E^2 - \boldsymbol{p}^2 = -m_{\rm o}^2$. See e.g. E.V.Shrum and K.O.H.Ziock: Phys. Lett. B37 (1971) 114; D.C.Lu et al.: Phys. Rev. Lett. 45 (1980) 1066; G.Backenstoss et al.: Phys. Lett. B43 (1973) 539; H.B.Anderhub et al.: Phys. Lett. B114 (1982) 76; R.Abela et al.: Phys. Lett. B146 (1984) 431; B.Jeckelmann et al.: Phys. Rev. Lett. 56 (1986) 1444.

From the theoretical point of view, about the above point see E.Giannetto, G.D. Maccarrone, R.Mignani and E.Recami: Phys. Lett. B178 (1986) 115-120, and references therein; see also ref.[10] and references therein.

Recent experiments showed that also *electron*-neutrinos result to have negative mass-square. See e.g. R.G.H.Robertson et al.: Phys. Rev. Lett. 67 (1991) 957; A.Burrows et al.: Phys. Rev. Lett. 68 (1992) 3834; Ch.Weinheimer et al.: Phys. Lett. B300 (1993) 210; E.Holtzshuh et al.: Phys. Lett. B287 (1992) 381; H.Kawakami et al.: Phys. Lett. B256 (1991) 105, and so on. See also the reviews or comments by M.Baldo Ceolin: "Review of neutrino physics", invited talk at the "XXIII Int. Symp. on Multiparticle Dynamics (Aspen, CO; Sept.1993); E.W.Otten: Nucl. Phys. News 5 (1995) 11. In very recent papers, J.Ciborowski and J.Rembielinski claimed to be able to explain a crucial experimental detail just by the Superluminal hypothesis ("An explanation of anomalies in the electron energy spectrum for tritium decay", Preprint submitted to HEP97–PA10#744; 1997); while S.Giani (IT, Cern) claimed that, for explaining the arrival times of the neutrinos (emitted by the 1987a supernova) detected by the Monte Bianco and Kamiokande experiments, Superluminal propagation speeds are in order.

Third: Galactic "Mini-Quasars", etc. (Apparent Superluminal expansions observed inside quasars, some galaxies, and –as discovered very recently– in some galactic objects, preliminarily called "mini-quasars") – Since 1971 in many quasars (and even a few galaxies) apparent Superluminal expansions were observed ["Nature", for instance, dedicated to those observations a couple of its covers]. Such seemingly Superluminal expansions were the consequence of the experimentally measured angular separation rates, once it was taken into account the (large) distance of the sources from the Earth. From the experimental point of view, it is enough to quote the book "Superluminal Radio Sources", ed. by J.A.Zensus and S.Unwin (Cambridge Univ. Press; Cambridge, UK, 1987), and references therein.

The distance of those "Superluminal sources", however, it is not well known; or, at least, the (large) distances usually adopted have been strongly criticized by H.Arp et al., who maintain that quasars are much nearer objects: so that all the above-mentioned data can no longer be easily used to infer (apparent) Superluminal motions. However, very recently, GALACTIC objects have been discovered, in which apparent Superluminal expansions occur; and the distance of galactic objects can be more precisely determined. From the experimental point of view, see in fact the papers by I.F.Mirabel and L.F.Rodriguez. : "A superluminal source in the Galaxy", Nature 371 (1994) 46 [with a

Nature's comment, "A galactic speed record", by G.Gisler, at page 18 of the same issue]; and by S.J.Tingay et al. (20 authors): "Relativistic motion in a nearby bright X-ray source", Nature 374 (1995) 141.

From the theoretical point of view, both for quasars and "mini-quasars", see E.Recami, A.Castellino, G.D.Maccarrone and M.Rodonò: "Considerations about the apparent Superluminal expansions observed in astrophysics", Nuovo Cimento B93 (1986) 119. See also E.Recami: ref.(10), and cf. R.Mignani and E.Recami: Gen. Relat. Grav. 5 (1974) 615. In particular, let us recall that a *single* Superluminal source of light would be observed: (i) initially, in the phase of "optic boom" (analogous to the acoustic "boom" by an aircraft that travels with constant super-sonic speed) as an intense, suddenly-appearing source; (ii) later on, as a source which splits into TWO objects receding one from the other with velocity $v > 2c$ [see the quoted refs.].

Fourth: Superluminal motions in Electrical and Acoustical Engineering – The "X-shaped waves" – This fourth sector is perhaps the most important one. Starting with the pioneering work by H.Bateman, it became slowly known that all the (homogeneous) wave equations —in a general sense: scalar, electromagnetic and spinor— admit solutions with subluminal ($v < c$) group velocities.(36) More recently, also Superluminal ($V > c$) solutions have been constructed for those homogeneous wave equations, in refs.(37) and quite independently in refs.(38): in some cases just by applying a Superluminal Lorentz "transformation".(10,39) It has been also shown that the same happens even in the case of acoustic waves, with the presence in this case of "sub-sonic" and "Super-sonic" solutions.(40) Particular attention has been called by the circumstance that some of the new solutions are "undistorted progressive waves" (namely, represent localized, non-diffractive waves). One can expect all such solutions to exist, e.g., also for seismic wave equations. More intriguingly, we might expect the same to be true in the case of gravitational waves too.

It is interesting to remark that the Super-sonic and Super-luminal solutions forwarded in refs.(41) —some of them experimentally already realized(41)— appear to be (generally speaking) X-shaped, just as predicted in 1982 by A.O.Barut, G.D.Maccarrone and E.Recami in ref.(42); so that now they have been preliminarily called "X-waves".

On this regard, from the theoretical point of view, let us quote pages 116-117, and pages 59 (fig.19) and 141 (fig.42), in E.Recami: ref.(10). Even more, see the abovementioned A.O.Barut, G.D.Maccarrone and E.Recami: "On the shape of tachyons", Nuovo Cimento A71 (1982) 509-533; where "X-shaped waves" are predicted and discussed. From

the quoted papers it is also clear why the X-shaped waves keeps their form while travelling (non-diffractive waves): a property that already resulted of high interest for electrical and acoustical engineering. New experimental and theoretical work is going on (e.g., by F.Fontana et al. at the "Pirelli Cavi", Milan, Italy; and by H.E.Hernández F. et al. at the F.E.E.C. of Unicamp, Campinas, S.P.); let us mention in particular that by P.Saari, H.Sõnajalg et al. at Tartu, Estonia [see e.g. Opt. Lett. 22 (1977) 310; Laser Phys. 7 (1977) 32].

Very recently, some further important articles appeared. Let us mention in particular that: (i) at Tartu (Estonia) they have confirmed the experimentally production of X-shaped (Superluminal) light waves, in optics: see P.Saari and K.Reivelt: "Evidence of X-shaped propagation-invariant localized light waves", appeared in *Phys. Rev. Lett.*, Nov.24, 1997; (ii) simultaneously, (non-truncated) X-shaped beams with *finite* total *energy* —expected to exist on the basis of ER— were mathematically constructed by I.Besieris, M.Abdel-Rahman, A.Shaarawi and A.Chatzipetros in the work "Two fundamental representations of localized pulse solutions to the scalar wave equation", to appear in *J. Electromagnetic Waves Appl.* (1998).

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